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Utilization of battery-electric vehicles in two-car households: Empirical insights from Gothenburg Sweden

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ABSTRACT

Two-car households with one conventional and one battery electric vehicle (EV) have an opportunity to partially circumvent the range limitations of a modest-range battery-electric vehicle through flexible use. To investigate the extent to which real-world households utilize this flexibility, we used from 20 two-car households in the Gothenburg area in Sweden, GPS data from before and during an EV trial in which the households were asked to temporarily replace one of their two conventional cars with a short-range EV for the duration of the trial. The actual household electric drive fraction, i.e., the EV distance as a share of the total two-car household driving distance varied between 30 and 70%, with a household mean of 47%. On average, this corresponds to 80% of the estimated potential household electric drive fraction during the trial. We quantify the flexibility in choosing the EV as the difference in distance between the potential, and the minimum needed, EV driving. For below-range (≤120 km) home-to-home non-overlapping trips, the households used 69% of that flexibility. For household trips that did overlap in time, they used 56% of the flexibility. Thus, the EV is the preferred vehicle, but the preference is less obvious for overlapping trips. Our analysis implies an even more dominant role for the EV in weekend driving. Further, although the pre-trial data showed a large difference in the household shares of distances driven between a (later in the EV trial) replaced "first" car and a replaced "second" car, this difference disappears when an EV replaces either one.

1. Introduction

Compared to conventional vehicles (CV), plug-in electric vehicles (PEVs) represent an alternative with the potential to reduce use of fossil fuels and emissions of CO_2 and other pollutants, especially in countries and regions with low-emitting electricity production (Nordelöf et al., 2014; Yuksel et al., 2016). The realization of that potential depends on the interrelations among vehicle movement patterns, battery size, charging options, and costs. The fixed cost of today's PEVs increases rapidly with battery size, often resulting in a relatively limited range in order to keep the initial capital cost down, at least where recharging is hampered by lack of infrastructure or limited charging rates. Furthermore, this range challenge tends to be aggravated with driving distance, while the PEV's operational-cost advantage over the CV means that the vehicle's value proposition increases with driving distance. All system studies devoted to the evaluation of PEVs have to deal with these trade-offs in one way or another.

For studies of plug-in hybrid electric vehicles (PHEVs), the *electric drive fraction* (EDF),[1] i.e., the share of the driving propelled by electric energy externally charged to the battery, is a central concept (SAE International, 2010; Paffumi et al., 2018). Researchers have

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[1] Also called utility factor (UF).

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estimated the *potential*, i.e., maximum, EDF for a given battery size and set of assumptions about charging infrastructure and behavior (for instance, once a day, or at home and at work) and various data on car movements, such as travel surveys (Lin & Greene, 2011; Gnann et al., 2015), probability density functions (Lin et al., 2012), and GPS-logged movements of conventional vehicles (Wu et al., 2015). By including cost estimates, some research has been able to derive (economically) optimal battery sizes and related *optimal* EDFs, either from a consumer or a societal perspective (Özdemir & Hartmann 2012; Neubauer et al., 2013; Lin 2014; Kontou et al., 2015; Björnsson & Karlsson 2015; Björnsson et al., 2018). Some recent studies have published *actual* EDFs for PHEVs estimated from various data on driving and energy use for real PHEVs (Smart et al., 2014; Tal et al., 2014; Plötz et al., 2017a, 2017b, 2018).

For battery electric vehicles (EVs), the EDF is naturally equal to one. Instead, a reasonable and commonly used indicator in EV analyses is the number of *days requiring adaptation* (DRA), i.e., the number of (annual) days for which an EV with a certain range is not able to cover a certain movement pattern given a set of assumptions about charging (Pearre et al., 2011). However, this is not a direct analysis of EVs. The movement patterns mostly come from conventional vehicles, which are implicitly assumed to represent some "unrestricted" driving needs. Once again, different kinds of sources have been used for the car movement data (Pearre et al., 2011; Kölbl et al., 2013; Tamor et al., 2013; Greaves et al., 2014; Jakobsson et al., 2016; Wu, 2018).

Modeling studies as depicted above, when estimating the potential EDF or DRA, have assumed that one PEV substitutes for one specific conventional vehicle. We therefore can think of the above concepts as the *vehicle EDF* and *vehicle DRA*. However, multi-car households make possible a flexibility and allow for a broader concept of substitution. By choosing a certain car for a specific trip, a PEV can be driven more than what is given by any single replaced car's movement pattern. It is then reasonable to think in terms of a *household EDF* and a *household DRA*, when a household has a PEV as (at least) one of its cars (Mandev et al., 2019). We can note that a household EDF is now non-trivial and relevant also for EVs.

Our prior work has shown that for two-car households in Sweden, this flexibility could represent a $7000 value. In other words, a two-car household could, all other things being equal, pay that much more for an EV compared to a one-car household (Karlsson, 2017). On average, the two-car household can drive more on electricity, which is cheaper than driving on gasoline or diesel, and, by relying on the CV for longer trips or trip chains, avoid costs of possibly unfulfilled car mobility due to the EV range constraint, using a smaller and thus cheaper battery. These three factors were estimated to contribute roughly equally to the total value indicated above (Karlsson, 2017). The study was based on car movement patterns derived from GPS data for around two months in 64 commuting two-car households in the Gothenburg region in Sweden.

Although based on real driving data, the study was a modeling study of the potential options for an EV. But the question remains to what extent two-car households actually utilize these advantages and, therefore, what the actual household EDF is, in comparison to the potential household EDF. Even if cost minimization favors maximizing EV driving, other factors could prevent full use of that potential. For instance, some driving may require specific equipment that may only be available in the non-EV, such as a tow bar or a child seat. The non-EV may also be preferred for some driving for safety, reliability, or capacity reasons. Psychological factors such as "my car and your car" and ordinary habits that evolved when only conventional vehicles were available may inhibit the use of the cars for maximum EV driving. Or households may simply not be sufficiently motivated to put the effort into maximizing their EV use, because that could require daily considerations and decisions about who will use which car, when, and for what, that is, about factors sometimes unknown in advance.

To our knowledge, there are no published studies that actually measure and evaluate actual EV driving in comparison to what in principal could be achieved in multi-car households. Only two studies other than Karlsson (2017) have analyzed PEV options based on simultaneous logging of movement data for both cars in two-car households with two conventional-fuel cars. Using data from the Seattle region, Tamor and Milačić (2015) concluded that an EV with a modest range (160 km) appears to be viable at costs that are likely to be achieved in the near future. Using the same data set as Karlsson (2017), Björnsson and Karlsson (2017) compared substituting a PHEV, for one of the two-car households' vehicles, to substituting an EV, concluding that when fully utilizing the flexibility, an EV is more economically viable but achieves a somewhat lower household EDF.

Others have used logged data from two-car households, but specifically only estimated the potential for an EV when it substitutes for the driving pattern of one of the two cars, focusing on the estimated vehicle DRA, not allowing for the EV to play a more flexible role. Using the same Seattle data set as Tamor and Milačić (2015), Khan and Kockelman (2012) found that an EV (160 km range) that replaces (only) the least-driven car in a multi-car household would reach the range limit less often than in a single-car household. Based on GPS data from one car in various single- and multi-car households with conventional cars, Jakobsson et al. (2016) showed that the number of DRA would generally be lower when an EV replaces the "second car" (i.e., the one with the less annual driving) compared to the "first car" in two-car households as well as to the single car in single-car households. The study also concluded that the EV economics on average favored replacing the second car.

In this paper, we present an analysis EV utilization in two-car households based on an EV trial. The overarching research question is: To what extent do two-car households having an EV utilize the available flexibility given by the movement patterns of their cars? In Chapter 2, we present the trial project and develop the measures/indicators used for the analysis of the available flexibility and its actual utilization. The results of this are presented in Section 3.1. In Section 3.2 is given the implications of the utilization for the distribution of the use of the cars during the day and the week. In Section 3.3, we present which car the households replaced by an EV, and we investigate whether the flexibility utilization was copied from the driving of the replaced car or if a new car movement pattern of the EV was established. Finally, Chapter 4 contains a discussion and conclusions.

2. Methods and data

2.1. The EV trial period and data

In 25 of the 64 two-car households with two conventional cars involved in the above-mentioned GPS-tracking project (Karlsson, 2017), we have in a subsequent EV trial project again tracked both vehicles for around three to four months but now after one of the conventional cars was replaced by an EV, a 2015 Volkswagen e-Golf. In these two separate projects, hereafter called the pre-trial and the (EV) trial project/period, respectively, we thus have data on car movements from both before and after the replacement of one of the cars with an EV. However, the data are only of high quality in 20 of the 25 households, due to unsuccessful logging. Therefore, we only utilize data from these 20 households in the analysis of EV options and usage.

The 64 pre-trial households had accepted to participate in the logging of their cars after being randomly selected from vehicle registry. We required they should have exactly, and only, two private cars,[2] and car owner(s) to be <65 years old. Their two cars should both be <10 years old, weigh ≤2000 kg, and have a rated engine power of ≤200 kW. In the region there were in total 332 000 private cars, of which 48% and 33% in households with 2+ and 2 private cars, respectively.[3] The further restrictions reduced the applicable cars to 11% in 18 500 households of which 3358 were randomly inquired for participation. With the inquiry we further required at least two actively used driving licences, and commuting with one car at least 10 km one way. 128 households, i.e., around 4% the inquired, fitted and accepted, and had logging equipment installed. In 64 of these the delivered data were of acceptable quality for the analysis of EV options in two-car households (Karlsson 2017).

There is no socio-economic statistics specifically for two-car households in general in Sweden. Further, this study is on detailed driving patterns of two-car households, where the only data are the 64 households in Karlsson (2017), from which "our" 20 households were taken. Our 20 households do not differ significantly (Wilcoxon rank sum test) from the residual 44 (=64–20) concerning extrapolated measured annual mileage, stated commuting distance, and household and car composition. The selection goes towards somewhat younger car owners, though: in the 20 EV households and in the 64 households they are on average 3.3 and 2.0 years younger, respectively, than in the inquired 3348 households. There is no similar tendency in the car properties age, weight, power, and specific fuel use.

For this EV-trial project, households were selected from the 64 households in the pre-trial project based on a combination of earlier data and interviews. The intention was to get a broad distribution of various factors such as household size, car properties, commuting distances, and charging options at work. Inclusion required both easy installation of home charging equipment and no significant changes to overall movement patterns since the pre-trial data collection, such as a change in commuter distance. Of the households finally offered an EV-trial period, almost all accepted.

The trial period was meant to mimic as closely as possible the situation in which the households had EVs of their own. No specific use of the EV was suggested, and the households had to plan and facilitate their mobility themselves.

Home charging equipment was installed in a suitable place. All households were then able to charge with 230 V 16 A, corresponding to a charging power of roughly 3 kW at the EV battery. Some households also had the option to charge at the workplace. In some households other occasional charging also took place.

Each household had to choose one of their CVs to park for the duration of the trial period and promise not to use it (except for any necessary service or compulsory vehicle inspection). The parked car was checked for any use during the trial period. The economics should preferably reflect the short-term operational economics when owning an EV. Thus, the households paid for the electricity charged at home, parking costs, and congestion charges in Gothenburg, as well as any traffic and car insurance deductibles.

The trial period should be long enough to well transcend any initial EV excitement and unfamiliarity and include a variety of driving situations. The trial was distributed across three separate periods: March-September 2015 (10 households), October 2015-January 2016 (10 households), and March-June 2016 (5 households). The trial thus covered different seasons, including vacation and holidays periods, as well as winter conditions with colder weather and driving with studded tires. Due to problems with the measurement equipment, only five of the ten households in the first period are included in the movement pattern analysis here and also only from April/May 2015 and on. However, for any given household, the time of year for the pre-trial data collection need not match the time of year for the EV-trial period.

During the trial period, GPS data were logged (1 Hz), giving the position and speed of both cars simultaneously. For the EV, the odometer reading, speed, state of charge (SoC), and outdoor temperature were also extracted from the on-board diagnostics. Date and time and electricity (kWh) for each charging session were retrieved from the home charging equipment. Semi-structured interviews with the household members were performed before and at the end of the trial period. Here we only use trip-level data in the form of trip distances and trip start and stop times, although other data have been used for control and filtering. For instance, GPS distances have been checked for consistency with the odometer readings.

[2] Thus, no households with a company car were participating. The vehicle registry does not identify households having company cars, why we chose to omit them.

[3] There are also multi- and two-car households having one or more company cars. Altogether multi-car households should contain over 50% of all privately used cars.

2.2. Assumptions and modeling

The analysis of the potential and actual utilization of the EV is done as an ex-post analysis of the scrutinized trip data from the trial period. We use previously developed optimization programs to estimate the maximum (i.e., potential) EV driving distance considering the movement patterns of both cars as well as the charging and range limitations of the EV (Karlsson 2017). In the optimization, we assume that the cars can only be "exchanged" when they are at home simultaneously. Therefore, we merge trips into home-to-home trips (hth trips); i.e., the distances for all separate trips between leaving the home and coming back are added up to an aggregated hth trip distance, and the corresponding start and stop times are generated.

The model only takes into account charging at home. Earlier, we have shown that charging rate limitations are of minor importance compared to range limitations (Karlsson, 2017). Therefore, although the optimization programs can consider different charging rates, here we assume a much higher charging rate at home than the actual one in order to avoid a mixture of restrictions (i.e., from both charging rate and range) on potential driving.

The range of an EV depends on the specific energy use. During the trial, the specific energy use varied considerably across trips and was generally higher during cold weather periods and when driving with studded tires. It was often higher in the beginning of trips and after a longer parking time. Therefore, shorter trips often had higher specific energy use than longer ones. These e-Golfs have a 24.2 kWh battery and an average logged energy use during the trial of 18.3 kWh per 100 km. With an assumed 90% utilization of the SoC, this average energy use corresponds to a range of 119 km. Fig. 1 shows how far it was possible to drive the EV from the beginning of each trip utilizing 90% of the SoC estimated using actual specific energy use for consecutive trips. The average range is here 121 km.

In the modeling, the potential EV driving is estimated for assumed ranges varying in 11 steps from 60 to 500 km. An additional twelfth range denoted *Inf* (for *infinite*) is deliberately set so high that all actual hth distances are below that range. Due to the measured average range for the used EV above, the analysis includes a special focus on hth trip distances ≤120 km.

2.3. Analysis

The modeled potential EV driving distance varies with household car movement pattern due to two basic constraints: trips can overlap in time (the overlap constraint), and the EV has a range (the range constraint).

The overlap constraint. In a two-car household, the car movement patterns consist of a combination of single (non-overlapping) and overlap trips (Karlsson, 2017), see also Fig. 2. Trips that overlap in time will inevitably preclude the use of a given car for some portion of the driving, even if all trips are shorter than the EV range. The car cannot be in two places at once. The greater the share of overlap driving, the more limited the potential EV driving share of total household driving, all other things being equal. Further, the smaller the difference between the longest and shortest overlap driving, the less the scope of flexibility and the less it will matter that there is a choice of which car to use for which leg between common stops. We here define a leg as the sum of the hth trips for one car between common stops.

The range constraint. Assuming charging only takes place at home, hth trips above the EV range cannot be performed by the EV. The greater the EV range, the less this will matter, and the flexibility option in two-car households can mitigate the constraint. In reality, longer-than-range trips will of course be possible by using other charging options, such as destination charging and fast charging. In the EV trial, several households used a variety of charging locations, and the actual EV driving includes longer-than-range hth trips.

In two-car households, when a hth trip does not overlap in time with another, we call the trip a *single* trip, and the relevant driver can choose between both cars. This is a "one-person choice." When two or more hth trips between common stops at home overlap in time, we call them *overlap* trips and the two drivers have to jointly decide who drives what car; this is a "two-person choice," see Fig. 2.

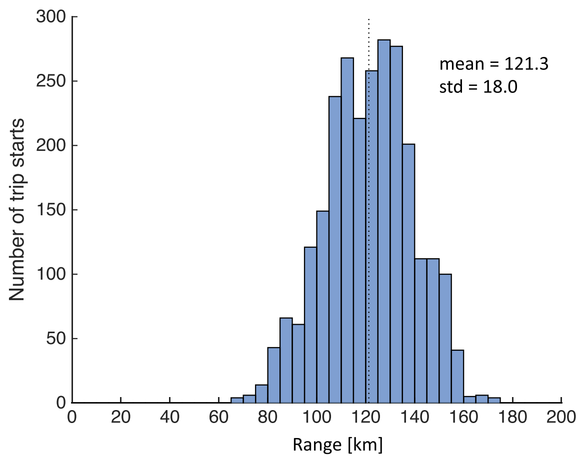


Fig. 1. Estimated range (interpreted as requiring 90% of actual SoC) at start of each EV trip as measured by actual average specific energy use for consecutive trips.

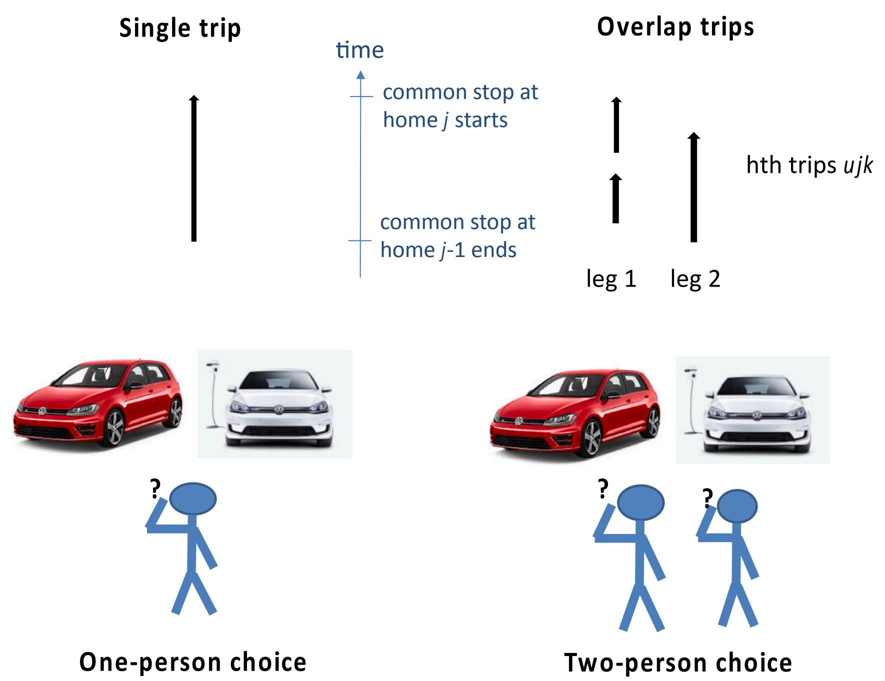


Fig. 2. In two-car households, when a hth trip does not overlap in time with another, we call it a single trip, and the relevant driver can choose between both cars, here, the "one-person choice." When two or more hth trips overlap in time, the two drivers have to jointly decide who drives what car, here, the "two-person choice." The index *ujk* is used for hth trip *k* of car *u* between common stops at home *j*-1 and *j*. An example of overlap trips shows two trips by one of the cars (leg 1, left) and one trip by the other (leg 2, right).

For single trips, only one car is needed between two common stops at home for the two cars. The question for the relevant driver is which car to choose for this trip, the EV or the CV. For overlap trips, two drivers simultaneously want to drive in overlapping hth trips and therefore have to somehow distribute the household's two cars among themselves. As indicated in Fig. 2, the number of overlapping trips in a leg can be more than one. Therefore, more planning may need to go into the car choice than a quick decision at the parking spot. For instance, the start times for overlapping trips may differ. However, even for single trips, the intentions of the other driver may need to be known in order to, for instance, know that it is indeed a single hth trip.

Car choices need to consider the range and home-charging-only constraints for the EV, yielding the possible combinations of hth trips depicted in Fig. 3. Dark blue (boxes 1a,b) and dark red (boxes 2a,b) represent single hth trips, where blue ones have distances below an assumed EV range *r* and give rise to a possible choice of car, while red are above the range and must (in the modeling) be performed by the CV. Light colors represent overlap trips. Light blue (boxes 3a,b) represents the driving done by each car between two common stops at home—the respective *legs*—consisting only of hth trips that are all below the EV range *r*, theoretically allowing for a choice of who drives which car for the period of time between these two common stops. In the light red boxes 4 and 5, one car, or one person, rather, has a hth trip that is greater than the range *r*. Therefore, in the modeling, the EV has to be assigned to the person whose hth trips for that leg are all below range. This means that the modeled EV in some cases has to take the shorter leg distance (boxes 4a,b), and in others the longer (boxes 5a,b). Occasionally, both drivers simultaneously have hth distances exceeding r, boxes 6a,b, which in the modeling results in an unfulfilled driving distance equal to the shorter leg between the common stops. The actual EV will instead have driven a hth trip longer than range *r*. Probably it has then charged outside the home, which is the case for the actual driving in boxes 4b and 5a, as well as 2a, too. In the further analysis, we group the driving in four groups (corresponding to the different colors in Fig. 3): single trips below range *r* (boxes 1a,b), single trips above range *r* (boxes 2a,b), overlap trips below range *r* (boxes 3a,b), and finally, overlap trips with at least one car's trip above range *r* (boxes 4a,b-6a,b).

We define a potential household EDF in each household, $potEDF_H$, by assuming home-charging only, and therefore including in the possible EV driving only driving between common stops at home for which all hth distances are equal to or below hth distance *D*

$$potEDF_H(D) = maxVKT(D)/hhVKT \tag{1}$$

where VKT is vehicle kilometers traveled, and where the maximum possible driving for a vehicle is

$$maxVKT(D) = \sum_j \left(\max_u \left(\sum_k d_{ujk}\right)\right) \quad \text{where} : d_{ujk} \leq D \tag{2}$$

and the total household driving is

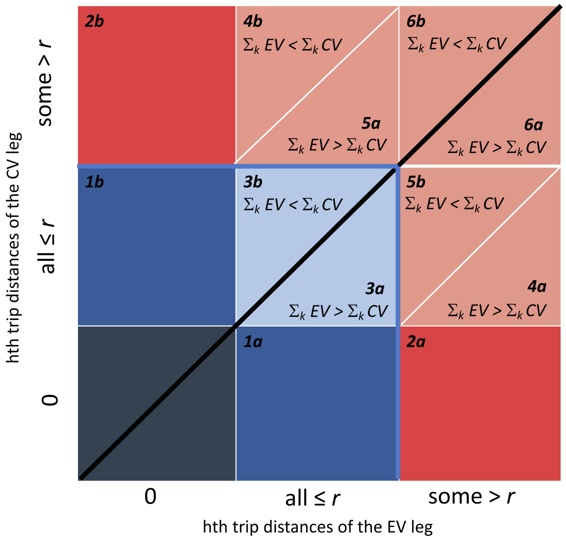


Fig. 3. Different possible combinations of hth distances for the two cars' actual driving between two successive common stops at home in a two-car household with one CV and one EV with an assumed range *r*. Inequalities in the boxes represent the relation between the EV's and the CV's sums of hth trip distances, respectively, between common stops (=leg distance).

$$hhVKT = \sum_{ujk} d_{ujk} \tag{3}$$

for hth distances d_{ujk} for the driving of vehicles $u = [CV \text{ and } EV]$ on hth trips $k = [1, K_{uj}]$ between common stops at home j-1 and j, where $j = [1, J]$. Here we can identify the overlap constraint (the limitation posed by overlap trips), $hhVKT$ – $maxVKT$(Inf), and the range constraint, $maxVKT$(Inf) – $maxVKT(D)$, respectively. The overlap constraint also yields the minimum driving required for the less driven car, $minVKT$(Inf). The actual household EDF, $actEDF_H$, is

$$actEDF_H = act_{EV}VKT/hhVKT \tag{4}$$

where the actual driving of vehicle u is

$$act_uVKT = \sum_{jk} d_{ujk} \tag{5}$$

To investigate the actual use of the EV in comparison to the potential use we formulate a utilization index for the household EDF

$$edf_HUI(D) = \frac{actEDF_H}{potEDF_H(D)} = \frac{actVKT_{EV}}{maxVKT(D)}. \tag{6}$$

A real choice of car can only occur when all hth trips between successive common stops are below range, that is, for driving in boxes 1 and 3 in Fig. 3. The flexibility or the scope of choice in driving for a given range D, $flxVKT(D)$, is defined as

$$flxVKT(D) \;=\; maxVKT_f(D) - minVKT_f(D) \tag{7}$$

where

$$maxVKT_f(D) = \sum_j (\max_u (\sum_k d_{ujk})) \quad \text{for } j : \forall d_{ujk} \leq D \tag{8}$$

$$minVKT_f(D) = \sum_j (\min_u (\sum_k d_{ujk})) \quad \text{for } j : \forall d_{ujk} \leq D. \tag{9}$$

We formulate an index for the utilization of the flexibility for a vehicle u, $flxUI_u$, in each individual household and separately for single and overlap trips, Eq. (10). The index varies linearly with the vehicle's actually driven distance between the end values of 0 and 1 corresponding to minimal and maximal possible use of a vehicle on driving, for which all hth trips between successive common stops are below or equal to D km:

$$flxUI_u(D) = \frac{act_uVKT_f(D) - minVKT_f(D)}{flxVKT(D)} \tag{10}$$

where

$$act_u VKT_f(D) = \sum_{jk} d_{ujk} \quad \text{for } j : \forall d_{ujk} \leq D. \tag{12}$$

For the indices

$$flxUI_{EV}(D) \;=\; 1 - flxUI_{CV}(D). \tag{13}$$

The index is thus equal to 0.5 when total actual hth driving distances $act_u VKT_f(D)$ for the two cars in the household are equal on the hth trips possibly driven by an EV with an assumed range D.

3. Results

3.1. Car movement patterns and potential EV driving

We first look at the constraints on car utilization created by the car movement patterns. Fig. 4a shows the potential EV-driven distance for each household, given the constraints posed by overlap trips and an EV range of 120 km with charging constrained to at-home only, as (extrapolated to)[4] annual kilometers, *maxVKT*(120), and Fig. 4b shows that distance as a share of total household driving, i.e., the potential household electric drive fraction, $potEDF_H(120)$.

The mean annual total household driving, *hhVKT*, is 34,300 km, while the average annual potential EV distance, *maxVKT*(120) is close to 20,000 km, varying from a low of 11,300 km to a high 36,500 km, see Fig. 4a, which corresponds to an average daily distance of 31 and 100 km, respectively. The latter number thus corresponds to 83% of the assumed EV range of 120 km.

As can be seen, the potential EV driving generally increases with total household driving ($r = 0.77$). The average overlap constraint and average range constraint are roughly the same, around 7000 km/yr. But while the overlap constraint tends to increase with total household driving ($r = 0.73$), the range constraint is relatively uncorrelated ($r = 0.23$).

The overlap constraint share of total household driving is between 10 and 32%, see Fig. 4b. This limits the potential driving of any car to on average around 79% of the total household driving, with an interval of 68 to 90%. The minimum or necessary driving for a car, *minVKT*(Inf), is given by the overlap constraint, and thus also varies between 10 and 32%. However, some of this minimum driving is possibly above the EV range, which occurs when between two common stops both drivers have hth trips exceeding the EV range, i.e., driving corresponding to box 6 in Fig. 3.

The range constraint share represents a more widely varying share of the total household driving, between almost zero and 50%. It is the dominating factor behind the inter-household variation in the potential household electric drive fraction, or $potEDF_H(120)$, which runs from a low of 38% to a high of 77%, with a mean of almost 59%. Also, while $potEDF_H(120)$ is strongly correlated with the range constraint share ($r = -0.88$), it is not correlated with the overlap constraint share ($r = 0.27$). We can also note (see *maxVKT*(180) = $potEDF_H(180)$ in Fig. 4b) that the driving patterns are such that a 50% increase in EV range will increase the potential EV driving fraction only marginally in most households, or on average by 2.8 percentage points. This increase corresponds to only around 14% of the range-induced constraint on potential EV driving, i.e. 14% of *maxVKT*(Inf) - *maxVKT*(120).

While the annual total household driving varies by a factor 2.5, between 22,000 and 55,000 km, it does not seem to significantly influence the potential electric drive fraction or its constraints ($|r| \leq 0.21$). Here, thus, the household driving pattern, rather than the total distance driven, has the greater effect on the potential electric drive fraction $potEDF_H(120)$.

Overlap trips represent two-thirds of the average total household VKT, see Fig. 5a. For hth trips within the assumed EV range, overlap trips represent a somewhat greater share or about 72% of the distance traveled. The potential EV driving distance is greater for overlap than single trips, too. But the difference between potential and necessary EV driving—the flexibility—is less for overlap trips and only accounts for on average 29% of the overall overlap trip distance. Between common stops, the longer leg is on average almost twice as long as the shorter one (65% and 35% of the distance between common stops, respectively), for overlap trips.

The share of above-range driving (driving where at least one of the two legs between common stops at home includes an above-range hth trip) is much less for overlap trips than for single trips (19% compared to 35%). Also, the due to overlap necessary driving is relatively short, which can be interpreted as that driving of distances above range simultaneously with both cars does not occur that often, which also was concluded in (Karlsson, 2017). This can be understood if above-range driving involves joint household activities such as weekend or vacation travel, during which the other vehicle remains stationary at home. Actually, some or most of the necessary driving can be hth trips shorter than the range (compare categories 4 and 5 in Fig. 3). In Fig. 5a it can be seen that on average these possible below-range distances are very small compared to all distances below range (≈3%).

As already noted, the constraints on movement patterns differ considerably between the households, see also Fig. 5b. The share of the driving above the EV range varies from very low (households 6, 9, 17, 18), to almost half (households 1, 3), to more than half (household 20) of the household's driving. For driving above the EV range, the distribution of distances between single and overlap trips is roughly the same on average, see Fig. 5a, with exactly 50% of the households having longer single trip distances, Fig. 5b.

For hth trip distances below the EV range, overlap driving exceeds single trip driving in all households but two (households 1, 14). The potential EV driving is dominated by overlap driving in 15 (75%) of the households. However, the flexibility in EV driving due to

[4] All extrapolation to annual values is a household-wise extrapolation in time: 365/trial period length (days).

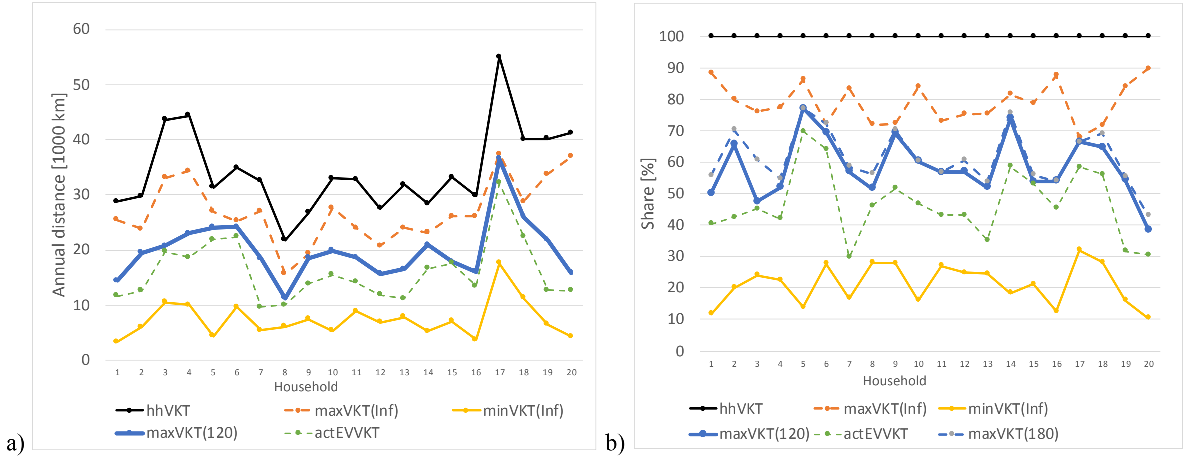


Fig. 4. a) The total (*hhVKT*), potential (*maxVKT*(120)), and actual EV ($act_{EV}VKT$) distances in the 20 households, along with the maximum (*maxVKT* (Inf)) and minimum (*minVKT*(Inf)) distances for a vehicle given an infinite EV range, all extrapolated to annual distances, and b) the share, for each variable shown in (a) plus for *maxVKT*(180), of the total vehicle distance traveled. The share for *maxVKT*(*D*) is equal to $potEDF_H(D)$.

choice of car (i.e., the difference between max and min) is considerably greater for overlap trips in only one household (19) and about the same as for single trips in another 5 (25%) of the households (households 2, 6, 7, 10, 15). For the majority of the households (70%), single trips clearly dominate the flexibility.

3.2. *Actual EV driving and flexibility utilization*

3.2.1. *Household electric drive fraction*

When extrapolated to one year, the actual EV driving, $act_{EV}VKT$, varies between 10,000 and 32,000 with a mean of 16,000 km, and follows the potential EV distance, *maxVKT*(120) to a high degree (r = 0.90), see Fig. 4a.

The EV fraction of total household driving, $actEDF_H$, varies between 30 and 70%, see Fig. 4b, with a household mean of 47%. In general, $actEDF_H$ increases with the potential household EV drive fraction, $potEDF_H(120)$ (r = 0.78). However, there are differences in the extent to which the households have utilized the potential; the EDF utilization index, $edf_HUI(120)$ varies between 0.52 and 0.99, with an average of 0.80. The corresponding unutilized potential driving, i.e., the difference between potential and actual EV driving, varies between close to zero and 9100 km/yr (mean 4000 km/yr). However, these unutilized kilometers do not correlate with either total household driving (r = 0.09) or potential EV driving (r = 0.12).

3.2.2. *Flexibility utilization*

Fig. 6 illustrates the actual utilization of the EV flexibility during the trial period, for single and overlap trips, respectively. In the single trip case, Fig. 6a, the flexibility utilization index, $flxUI_{EV}(D)$, shows that for hth distances up to $D = 150$ km, the EV is chosen for more of the possible distances than the CV in all but one (95%) of the households. The household-average utilization index at 120 km is 0.69. On average, the EV is thus used for 69% of the total below-EV-range single-trip household-weighted total distance. For an assumed "infinite" EV range, the utilization index is still above 0.5, meaning that for single trips, the EV has been somewhat preferred over the CV, when measured as actual distance driven, at the average household level.

For overlap trips, see Fig. 6b, the flexibility utilization varies extensively among the households; at 120 km, the index takes values roughly between 0.1 and 0.9, with an average of 0.56. Of the individual households, 12 (60%) have an index above 0.5 at 120 km. The mean index of 0.56 means that for overlap trips below the assumed EV range, around 56% of the household-weighted flexibility distance is driven by the EV. For longer distances, the average index gradually falls and goes below 0.5 at 400 km.

Both indices adopt their highest average values for distances below 60 km and then monotonically decrease with increasing hth distance *D*, i.e., the greater the distance *D*, the lower the household-weighted share of EV driven distance. In Fig. 6, the EV flexibility utilization below 120 km is on average greater for single trips than for overlap trips, with, as mentioned, average indices of 0.69 and 0.56, respectively. Due to the large spread between the individual households, especially for overlap trips, the difference is not significant at the 95% level: a two-sided Wilcoxon signed-rank test gives p = 0.057 for the difference.

The actual EV driving in the individual households is also given in Fig. 5b. The flexibility index is the actual EV driving share of the flexibility, the blue area. For hth distances ≤120 km, the index is independent of the flexibility for the overlap trips (r = 0.0), but weakly positively dependent for single trips (r = 0.442, p = 0.05).

3.2.3. *EV occupancy and daily distances*

According to Section 3.2, the EV and CV uses differ, such that the EV on average has a larger share of the hth distances driven below 120 km and also for single trips compared to the CV.

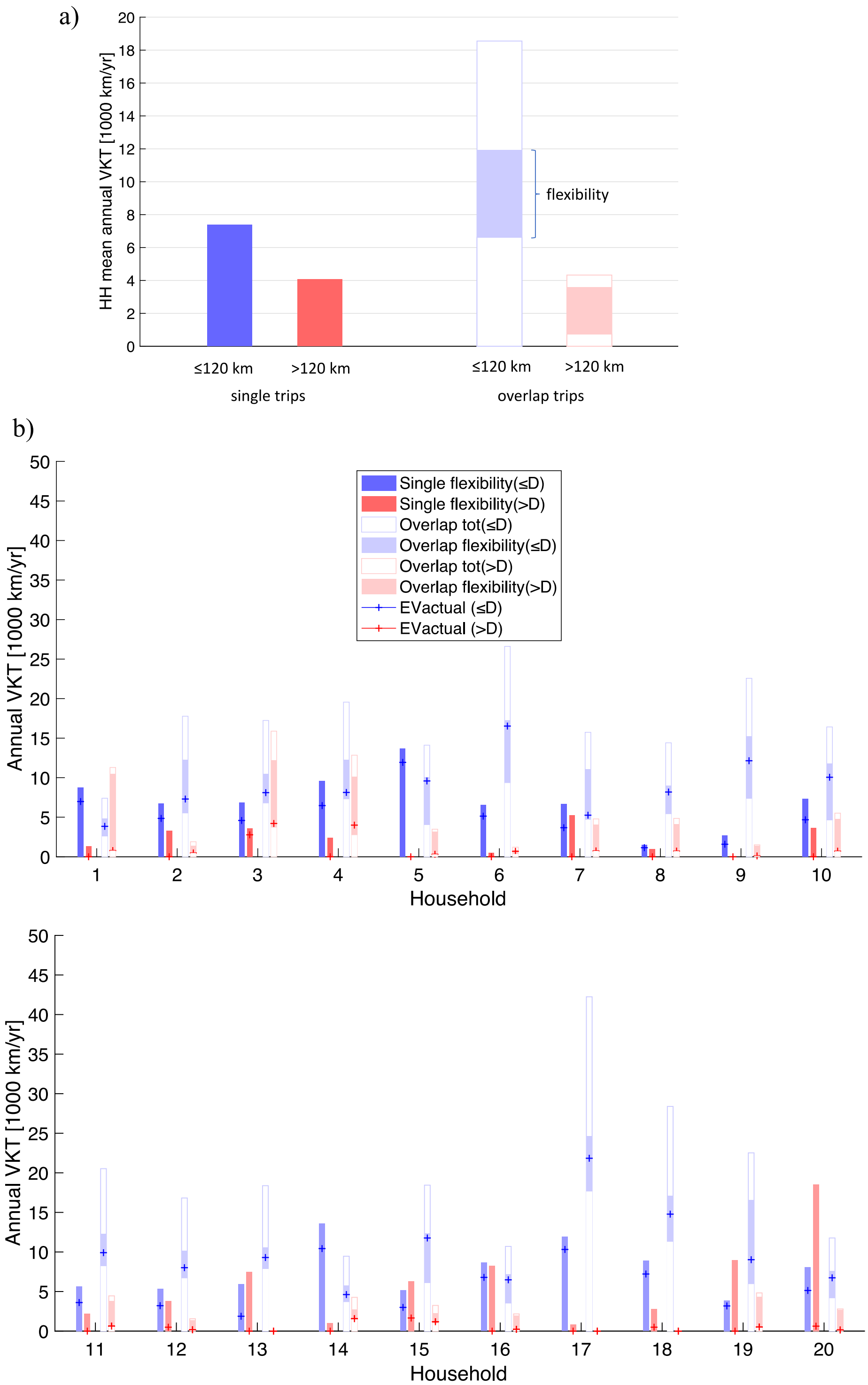
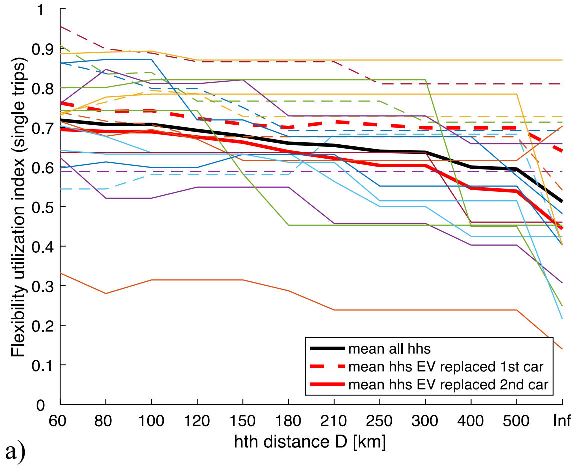


Fig. 5. The extrapolated annual driving in the households, divided into single and overlap trips, respectively, as well as into driving between common stops containing and not containing hth trips above a distance of $D = 120$ km for a) the average across households, and b) individual households. In each category, the shaded share shows the flexibility of the EV driving. The actual EV driving is depicted with plus signs.

How does this distribution affect the time of use of the EV compared to the CV, during the day and the week? There are two interesting perspectives on time of use. First, when is the car driven, i.e., when do its trips take place and when is it thus not parked? Second, when is the car occupied, i.e., when is it away from home, and therefore cannot possibly be used by another household



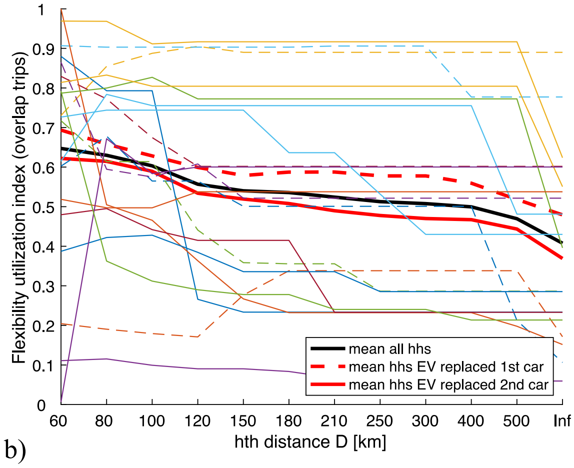


Fig. 6. Trial period flexibility utilization indices of EV use by hth distance *D* for a) single trips, and b) overlap trips. Thin lines, dashed: indices for households that replaced the first car; solid: indices for households that replaced the second car. For index definition, see text.

member and also, if an EV, cannot be connected to the home charging equipment? We introduce the *occupancy frequency* as the average daily number of times the car is occupied at different times of the day. Another interesting aspect is the intensity of use when occupied expressed as average away-from-home speed at different times of day, which we here denote the *occupancy speed*. The occupancy speed multiplied by the occupancy frequency gives the time of day distribution of *daily distances* driven when occupied or away from home. For a given distance driven, the higher the occupancy speed, the more the EV can be at home either for charging or for possibly being further utilized. Here, we therefore focus on frequency and speed of occupancy rather than use.

Fig. 7 shows time-of-day distributions for average occupancy frequency and speed and daily distances for the hth trips below the assumed EV range of 120 km.[5] We see in Fig. 7a, that on weekdays, overlap trips dominate the occupancy frequency. During the day, more than one car is away from home at the same time, on average. On the weekends, the cars are more occupied by single trips, though. Single trips also make up a higher share of the driving in the afternoons/evenings compared to daytime. The total average occupancy frequency for weekdays and weekends is 0.62 and 0.22, respectively, meaning that the cars are jointly away from home about 14.9 h (=0.62*24) and 5.3 h on weekdays and weekends, respectively.

The EV dominates the occupancy at any time of the day (Fig. 7b). It is away from home more than the CV on weekdays, and the relative difference is even greater on weekends.

Generally, the intensity of use when occupied is greater for single trips, on weekday evenings, and during the day on weekends, as illustrated in Fig. 7e, which depicts the average occupancy speed. The occupancy speed is about twice as high for weekend single trips as for weekday overlap trips. The occupancy speed is considerably lower during nights, reflecting the fact that shorter-than-EV-range overnight trips are combined with being away from home for a long time.

Combining the occupancy frequency (Fig. 7a) with the occupancy speed (Fig. 7e) gives the average distance driven when away from home, Fig. 7c. On weekdays, overlap trips dominate during daytime, but on evenings the single-trip distances are as great. On weekends, driving mostly consists of single trips, and especially so in the afternoon/evening.

The EV is used for most of the distance driven at (almost) all hours of the day both on the weekdays and (especially) on the weekends, Fig. 7d. However, we can also note that the increased share of single trips in afternoons/evenings on the weekdays is not transferred into more EV occupancy frequency or distance at these points of time. The average daily distance driven is 44.0 and 36.8 km/day on weekdays for the EV and CV, respectively, and the corresponding distances for the weekends are 29.1 and 16.1 km/day. The EV daily distance is thus 20% greater than for the CV on weekdays and 80% greater on weekends. In total, the EV and CV daily distances for hth distances $\leq$120 km, are 39.7 and 30.9 km, respectively.

The average occupancy speeds on weekdays are roughly the same for the EV and the CV, but slightly higher ($\approx$10%) for the EV on weekends. But due to the generally higher occupancy speed as well as the greater share of the driving taken up by the EV on weekends, the overall occupancy speed for the EV is about 4% higher than for the CV for hth trips below the assumed EV range of 120 km.

As a complement to Fig. 7d, Fig. 7f shows the driving between common stops that include hth trips longer than 120 km. On these trips, the CV performs the vast majority of the driving. Overnight trips are a large part of these longer hth trips. The average daily distances are 3.3 km and 20.4 km for the EV and the CV, respectively. The total EV and CV daily distances add up to 43.0 and 51.3 km, respectively. The EV thus covers 46% of the total driving in the nineteen households considered in this section.

A summary of the EV and CV mean daily driving is given in Fig. 8, showing the dominance of the EV for hth distances below 120 km, especially on weekends, and the very little EV driving above 120 km.

[5] One household with a lot of night-time commuting is excluded here in this section, due to its specific car movement patterns.

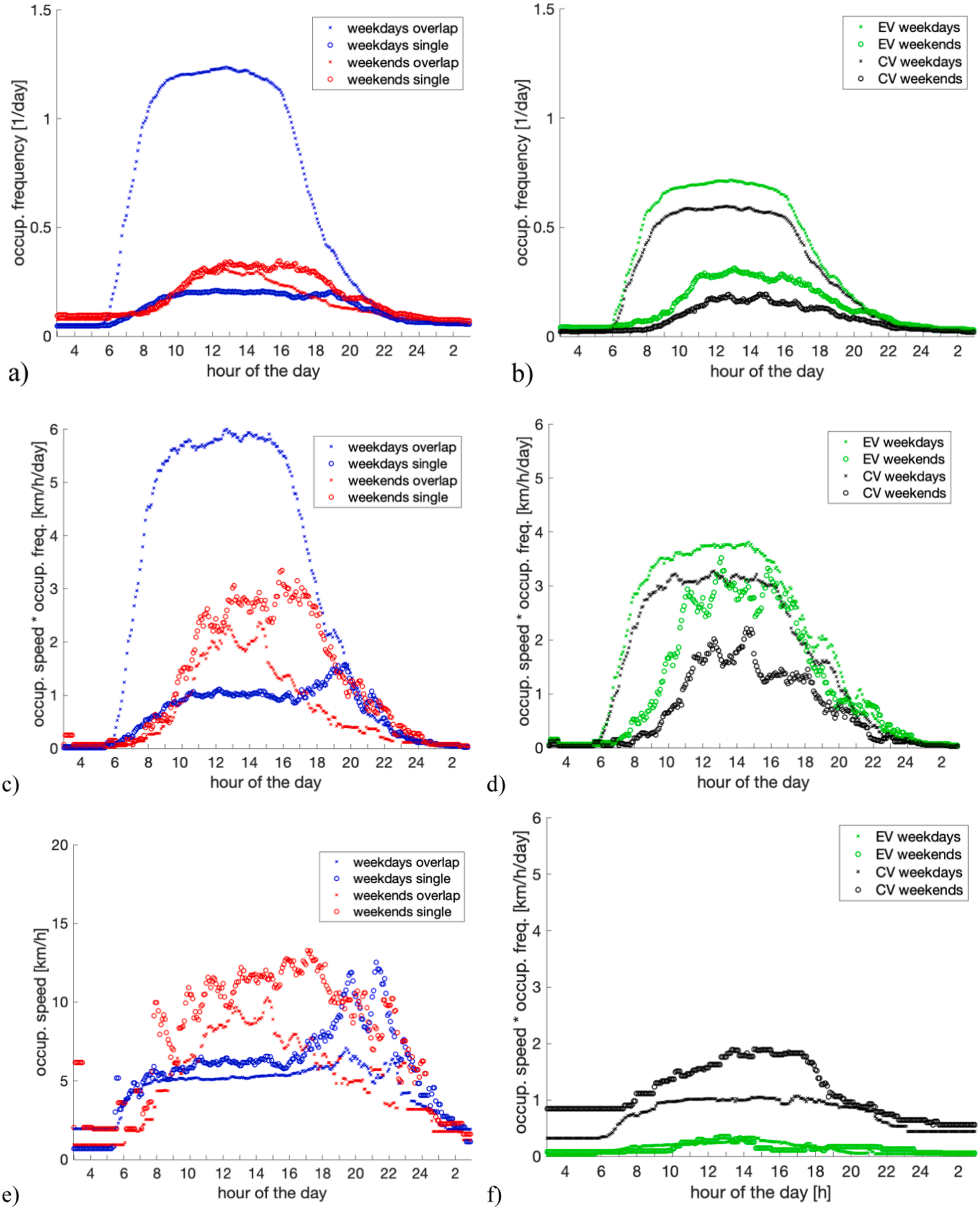


Fig. 7. For hth trips ≤ 120 km, time of day distributions for average occupancy frequency for a) single and overlap trips and b) the EV and CV; driven daily distances for c) single and overlap trips and d) the EV and CV and for e) average occupancy speed for single and overlap trips. f) For hth trips >120 km, time of day distributions of daily driven distances for the EV and CV.

3.3. *Heredity of car movement patterns?*

3.3.1. *The replaced car*

As mentioned, the households decided which car to replace with an EV. Does utilization depend on the which car was replaced? The

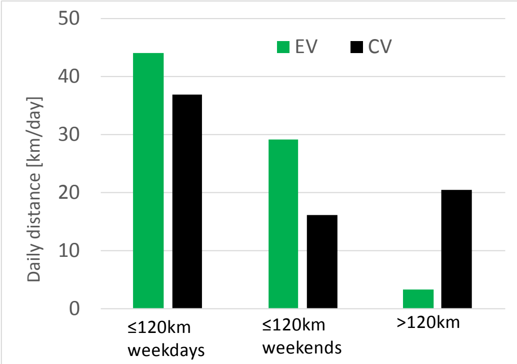


Fig. 8. Average daily driving distances for the EV and the CV.

choice of car can influence how a household coordinates driving needs and allocates driving to the two cars. For instance, car characteristics can make one car more suitable for certain trips or certain uses could be inherited with the car. The driving pattern of the replaced car could be passed on to the EV, preventing maximization of its use. So, which car was actually replaced? Table 1 shows how the actual household choices lined up with a variety of factors: car characteristics, movement patterns, and availability of charging at work. Only households with a clear difference in the investigated properties are included. For instance, households with cars of roughly the same size are excluded. Of course, the households are few and there are strong correlations between many of the factors. The following results should therefore be interpreted with care.

Tentatively, it seems that the car characteristics are the most influential; most households have chosen to keep the "better" car along the investigated car properties. The highest score, and also the only significant one, is for replacing the smaller car. Of households with a discernible difference in the size of their cars, about nine out of ten replaced the smaller car. Also, some car movement pattern properties were favored: fewer DRA and shorter annual VKT (vehicle kilometers traveled). The Gini coefficient is a measure of the confinement of the driving; a lower Gini coefficient corresponds to more hth distances in a narrower range and tends to favor the EV's economics for an appropriate EV range. Concerning infrastructure, only 5 (20%) of the households had stated that there was a charging option at work for exclusively one of the cars, but for those the correlation with car replacement was low.

3.3.2. *Movement patterns limitations*

The possible and actual EV driving may be affected by changes in driving patterns between the EV trial and pre-trial periods. Fig. 9 shows household driving distances, as well as overlap and range constraints, for the pre-trial and trial periods. The overlap constraint as share of total distance driven for the pre-trial period (shown in Fig. 9b) correlates quite well ($r = 0.66$) with that of the trial period. For the range constraint, the shares deviate strongly for three households (1, 14, and 20), while there is a reasonable correspondence between pre-trial and trial values for the rest ($r = 0.73$). Households 1 and 20 have little range-limited driving in the pre-trial period, while in the trial period there was more total driving as well as much more range-limited driving, see Fig. 9a. Household 14 shows the opposite pattern: there was considerably more total driving as well as more range-limited driving in the pre-trial period. Similarly, the shares of potential annual EV driving have a high correlation (0.83), when the same three households are excluded. However, the pattern of possible EV driving is reasonably preserved even when all households are included ($r = 0.67$), see Fig. 9a.

Table 1
Choice of car to be replaced in trial cross-checked against various factors: car characteristics, car movement patterns and car infrastructure.

Replaced car	Score	Share	Rank	Signif.
Car properties				
the *smaller car*	19 – 2	(90%)	1	**
the *older car*	15 – 8	(65%)	6	
the *non-diesel/E85 car*	10 – 3	(77%)	2	
the car with *no tow bar*	12 – 4	(75%)	3	
Car movement pattern properties				
the car with the *longer commuter distance*	11 – 10	(53%)	8	
the car with the *shorter annual VKT ("2nd car")*	12 – 6	(67%)	5	
the car with the *least DRA* (for 120 km hth distances)	14 – 6	(70%)	4	
the car with the *lower Gini-coefficient for hth distances*	16 – 9	(64%)	7	
Infrastructure properties				
the car with *charging option at work*	2 – 3	(40%)	9	

Score gives the number of households choosing the car with that factor versus those that chose to replace the other car. (Only households with a clear difference in that factor are included in the score, i.e., for instance, households with cars of roughly the same size are excluded.) Share is supporting share of scored households. Rank sorts the households from highest to lowest share. Significance level: * >95%, ** >99% (two-sided binominal, $p = 0.5$).

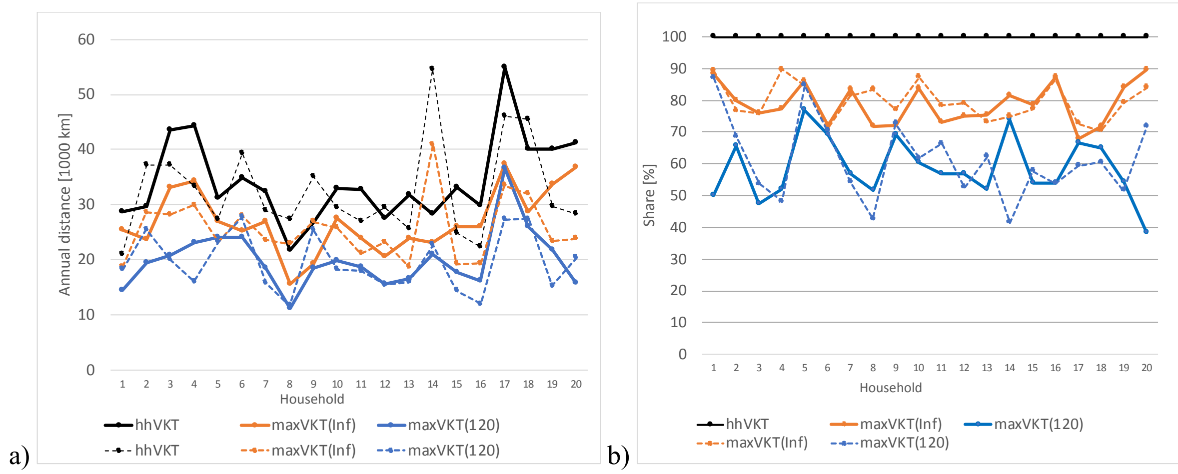


Fig. 9. Household driving in the pre-trial (dashed lines) and trial (solid lines) period, a) extrapolated annual distances, b) as shares of household driving.

3.3.3. EV use: nature or nurture?

We have seen that the EV is better utilized on shorter-than-range trips and especially so on single trips. But it is also reasonable to expect that the EV is driven as the car it replaces. Therefore, we ask, in the EV utilization, how much of the difference in the driving in the pre-trial period between the replaced first and second cars is transferred to the driving of the EVs?

In Fig. 6, the households were also grouped by whether they had chosen to replace the first (7 households) or second car (13 households). For car use with $D \leq 120$ km, the average EV utilization is greater for households replacing the first car, both in the single and overlap trips case. However, the differences are not that large, and also not really significant (for significance measured by $p < 0.05$) as indicated by a Wilcoxon rank sum test. (We do not assume the indices data to be normally distributed, and the number of observations is small, so use two-sided Wilcoxon rank sum and signed-rank sum tests on unpaired and paired households, respectively.)

Fig. 10 shows the corresponding utilization indices for the replaced cars in the pre-trial period. Here, the differences between the first and second car in average shares of the household driving are considerably larger, significantly so for overlap trips with around 0.47 index units in difference ($p = 0.0026$), but also for single trips (≈0.31 index units difference ($p = 0.13$)).

Fig. 11 compares household-average indices for the pre-trial and trial period. For single trips, the utilization has on average increased for both the households that replaced the first car ($p = 0.22$) and those that replaced the second ($p = 0.002$), leading to an overall significant increase of the utilization ($p = 0.001$). For overlap trips, the high utilization of the replaced first car in the pre-trial period (index ≈ 0.76) has not been transferred ($p = 0.03$) to the EV (index ≈ 0.60), while the low utilization of the replaced second car has increased ($p = 0.008$) considerably (from index ≈ 0.29 to ≈ 0.53). Taken together, the overall somewhat higher utilization for overlap trips therefore is not a significant change ($p = 0.19$).

Comparing the replaced car in the pre-trial period with the trial period EV reveals that overall the utilization index has increased on average almost 0.25 units (from around 0.45 to 0.69) for single trips and 0.10 units for overlap trips at hth distances up to 120 km. This means that the EV replaced a car that performed less than half of the driving, while the EV performs the majority of the driving, for trips up to 120 km.

But we can also see that the decrease in average indices with increasing hth distance is greater for the EV than for the replaced car, reflecting that the increased driving for the EV compared to the replaced car only holds for shorter hth distances. Overall, the EV's share of the households' total driving is 46.7%, while the replaced cars cover a little less than that of the pre-trial period's total driving (45.4%), so there is still an overall increase in the EV's share of total driving compared to the replaced cars.

In sum, the EV share of the driving is considerably greater than that of the car it replaced, for hth distances below 120 km, and the big pre-trial difference between first and second cars that were replaced has largely disappeared.

4. Discussion and conclusions

4.1. The project setup

Some attributes of this trial project deserve to be commented on. The households had not owned EVs previously. If they had, they would not have been a representative sample of the population at large. However, these households may be possible near-future EV buyers, i.e., early adopters, since they accepted having data from their CVs registered for EV research purposes and then accepted an EV trial period, which would also mean that they are not a representative sample. But that has not been the intention either: rather, already in the pre-trial project we have been trying to target potential suitable near-future buyers of a short-range EV, such as commuting two-car households in the surroundings of a bigger city. On the other hand, as discussed in Section 2.1, our selected households do not seem to deviate considerably in the available parameters from households in general with two private cars in the

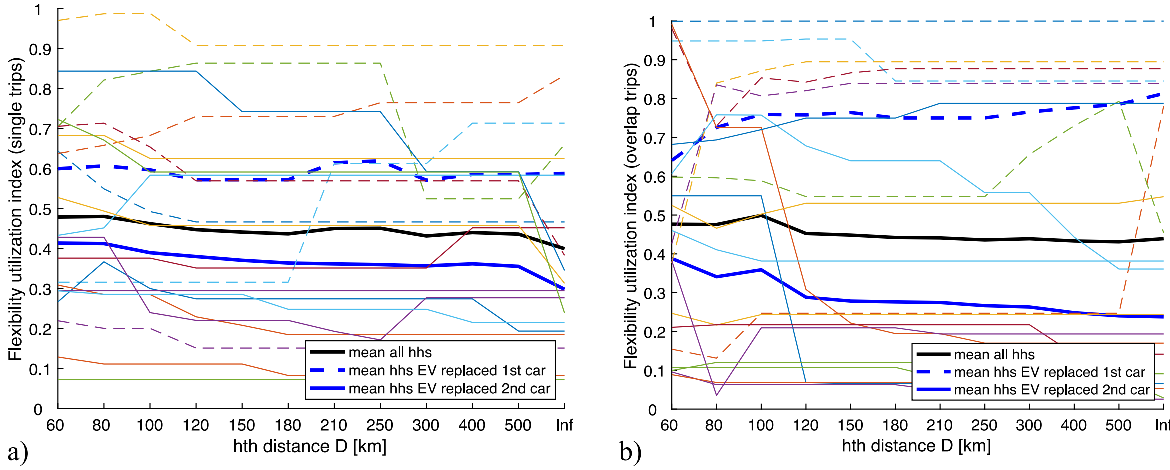


Fig. 10. The pre-trial period flexibility utilization indices of the replaced car in the different two-car households for a) single trips, and b) overlap trips. Thin lines, dashed: households that replaced the first car; solid: households that replaced the second car.

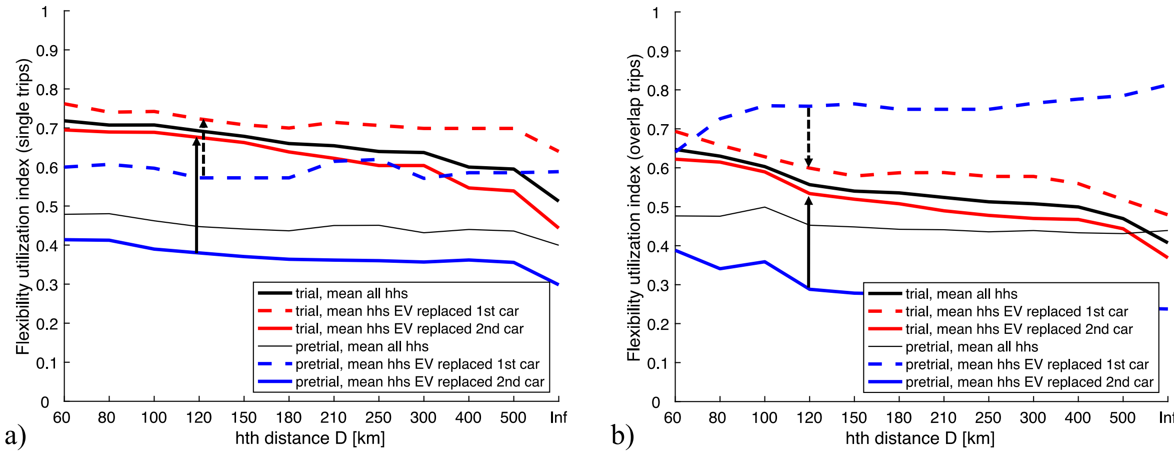


Fig. 11. The household-average flexibility utilization indices of the replaced car and the EV in the pre-trial and trial period, respectively, for a) single trips, and b) overlap trips. The arrows illustrate the average change in indices between the two periods in households replacing the first (dashed) and second car (solid), respectively.

targeted region.

Also, several factors particular to this trial project may have affected drivers' behavior. While the duration of the trial was meant to compensate for any initial peculiarities in order to allow the advantageous operational costs of EVs to register, the EVs did not belong to the households, and the drivers knew the experience was limited in time. The marginal cost of driving the EV was lower than what could be expected for future private car drivers: the households did not pay for the mileage depreciation of the EV, and some households could charge at work, probably for free. The EV was new and with a specific design, while the replaced cars were older and of various models. Both these last relationships could encourage increased EV driving.

Further, our modeling analysis is based on some assumptions and simplifications. We assumed an EV range of 120 km, although the estimated real range varied considerably, as shown in Fig. 1. The perceived real range can vary quite a lot across households and under various conditions. This may have led to an overestimate of the potential EV driving and therefore an underestimate of the actual utilization of this potential. Also, we assumed all charging took place at home. In reality, many households charged the vehicles outside the home, as seen in the SoC data. Including outside-the-home charging options in the estimate of the potential EV driving would increase it, which in turn lowers the value for the flexibility utilization. Neither was charging speed included as a limiting factor in the estimate of the potential driving. Previous analyses have shown that this may decrease the potential, but only to a minor extent (Karlsson, 2017).

Finally, the number of households is small, and we have seen that their behavior is quite heterogenous. While it is important to try to find significant relevant patterns in their driving, even though the sample is small, we do need to interpret the results with extra care.

4.2. The project results

The driving pattern limitations to EV driving are a combination of overlap and range limitations. Overlap is not much to do about. The range limitations varied substantially in between the households and were in general only little relieved by a 50% increase in range (Fig. 4b). So, is there any meaning with increased range? A longer EV range may contribute to relieving range anxiety and need for planning, which can be behind some of the non-use of the flexibility. Also, in colder climate as in Sweden, a longer range can compensate for range losses due to low outside temperature and studded tires. A somewhat longer range may thus contribute to, not so much a longer potential driving, but more actual EV driving. However, for the EV to comfortably take on also the longer trips, which contribute to a substantial share of the total driving in several of the households, a considerably longer range combined with a ubiquitous fast charging infrastructure is probably needed.

Concerning the actual EV driving, the most pronounced result is maybe the high utilization of the EV below range and the difference in flexibility utilization between single and overlap trips. Below 120 km, the EV drove more than two thirds (69%) of the single-trip distances, compared to 56% for overlap trips. Why this difference? Actually, most households claimed that the EV was their "first choice."[6] As concluded earlier, all but one household used the EV more than the CV for single trips below the EV range. For single trips, the "first choice" seems straightforward. But for overlap trips, the choice is perhaps less obvious. Ideally, the EV would be chosen for the longest hth trips, but both cars are often on overlapping trips that last for around 10 h. Perhaps this obscures the fact that the EV is not being used optimally; perhaps it is less obvious that the distance driven ought be maximized, not the time the vehicle is occupied. The choice of vehicle for overlap trips is also more complicated, involving coordination between drivers, more driving and errands, and maybe more habitual driving (daily commuting), etc.

The EV performed a major share of the below-range driving in the weekends. No such tendency was seen for the weekday evenings, although the single trip driving share was higher also for that period of time. This can partly be an effect of the limited range. EV driving in the evenings will most often involve starting with a lower battery SoC due to earlier daytime driving and a possible short stop before in combination with a low power rating of the home charging equipment. But before the weekend driving, the EV battery has most probably been filled up during the night.

With mostly only home charging, as in this project, the occupancy rather than the times of driving determines the possible time for charging and other interactions with the electricity system. With more public infrastructure and charging at work and other public places the specific times of driving will be more important. A more pronounced weekend driving for the EV, as detected here, will contribute to a leveling out of the electric load, and may thus be the case if multi-car households dominate the initial EV market.

Analyses of potential EV driving have so far been dominated by studies relying on the assumption that an EV substitutes only a specific single car. As demonstrated in this study, in two-car households, the potential EV driving exceeds that, as does the actual driving. Elucidation of the possible numerous, actual and household-specific reasons for the discrepancy between potential and actual driving have been outside the scope of this study, though. The EV driving differed from the driving of the replaced car. Specifically, when looking at the actually driven distances, very little of the replaced car, whether the first or the second car, was seen in the EV driving. Thus, considerations of the EV potential driving and economics and the possible needed ranges in the vehicle fleet must take into account the options in multi-car households, which today are ubiquitous in industrialized countries.

We report a tendency that which car to replace focused car properties, and the smallest and oldest was replaced, rather than driving patterns (such as second car replacement) and charging options. This makes sense in the perspective of their EV driving: the specific driving of the replaced car was not copied, and new patterns of car use were established to various degree. This seems also rational given that the households did not pay for the EV. But this last means that we should be careful about conclusions on how multi-car household prefer to substitute cars for an EV.

4.3. Some implications for the EV market

After an initial market period with mostly short-range EVs, there is currently an ongoing race toward larger batteries. But as we have shown, a small battery may be sufficient in multi-vehicle households, if the cars are used wisely. In the long run, the market will mature, more diverse models will be available, and buyers will be more aware of various EV properties and how they fit their car movement patterns. In the meantime, more public education on EV ranges and how they may fit into multi-car households can facilitate the EV market by increasing the acceptance of well-suited short-range and less expensive EVs.

Because of the current market tendency to favor the lower specific cost per battery of larger batteries, the market expansion problem due to high EV upfront costs has prevailed. The EV market is still largely dependent on push and pull forces. Currently, in the EU, the CO_2 regulation is a strong push on car manufacturers to sell more EVs to avoid severe fines (Transport & Environment, 2019). For potential EV customers purchase cost and range are the most important hurdles to wider consumer adoption (McKinsey & Company, 2017). Apparently, equipping EVs with smaller batteries for lower cost affects the range negatively. Thus, it should also be in the interest of car manufacturers to offer a range of battery sizes, and together with dealers to promote and market cheaper short-range EVs by highlighting the options in multi-car households.

Although more people and households can find an EV economically viable, they still have to finance the initial purchase.[7] The

[6] In this study, we have deliberately avoided using the interviews, but this is a minor exception.

[7] Private leasing could be an alternative. However, private leasing can be expensive as long as the leasing firms take into account both the higher capital costs and any perceived uncertainty about the secondary market for EVs.

combined age of the two cars in our 25 households varied between 9 and 23 years, with an average of 15.5 years. That is, these are not new cars. An EV purchased today is almost inevitably a new car and therefore involves a high initial cost compared to the value of these households' current cars. Households wanting to keep the capital cost of their cars down may need to combine a new EV with a (much) older and cheaper but otherwise versatile car. Buying a new EV while keeping overall car capital costs down may need to take the household vehicle fleet composition as a whole into account. This would increase the challenge of buying an EV.

In Sweden, tax rules are favorable to having a new car as a benefit car, contributing to over half of the new cars constitutes company cars (Engström et al., 2019). After some years these cars enter the second-hand market and are bought by mostly private persons. This may explain the relatively old cars seen in our households. It also means that how EVs are treated by the tax rules for company cars is important for the continued expansion of the Swedish EV market and the future availability of cheaper EVs in the used-car market.

Acknowledgments

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Glossary

CV: conventional vehicle, = a non-EV vehicle
DRA: days requiring adaptation, = number of days with driving longer than range
EDF: electric drive fraction
EV: battery electric vehicle
hh, hhs: household(s)
hth (trip): home-to-home (trip)
PEV: plug-in electric vehicle, = EV + PHEV
PHEV: plug-in hybrid electric vehicle
SoC: state of charge
(annual) VKT: (annual) vehicle kilometers traveled